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METHODS FOR MEASURING CHARACTERISTICS OF NIGHT VISION GOGGLES (U)

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FOR THE COMMANDER

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There are many parameters that are used to describe and specify night vision goggles (NVGs) such as resolution, field of view, brightness gain, distortion, etc. However, standardized test procedures for determining the value of these parameters have not been established. Informal comparison studies have shown that measurements of some of these parameters may vary considerably (as much as a factor of two) depending on the method, equipment, and procedures used to make the measurements. The purpose of this technical report is to document specific procedures for measuring most of the major parameters used to specify NVGs to help standardize methodology and improve accuracy and comparability between measuring organizations.

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PREFACE

The work described in this technical report was funded under Program Element 62202F Project 7184-18-07 entitled "Night Vision Devices" and Program Element 63231F Project 3257 entitled "Helmet-Mounted Systems Technology" (HMST). The primary purpose of this report is to document the night vision goggle (NVG) measurement methods that have been developed to quantify the performance of the NVGs. The motivation was to develop standardized procedures that could be used for any NVG without dissecting the NVG and measuring the component parts. These methods were used to evaluate the I-NIGHTS night vision goggles/helmet-mounted displays developed under the HMST program. These procedures are still being developed and the reader should understand that some of these procedures may be modified in the future to improve their accuracy, repeatability, and/or utility.

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INTRODUCTION

Night vision goggles (NVGs) have become a key technology for fighting and flying at night in both fixed wing and rotary wing aircraft. With the success of NVG technology came a flood of NVGs in different configurations designed to improve their characteristics. In order to evaluate these different NVG designs it is highly desirable to have a collection of standardized measurement procedures to permit critical comparisons between devices. The purpose of this report is to document some of the measurement procedures that have been developed to assess the characteristics of night vision goggles. In each case it is assumed that the NVG cannot be disassembled, which would permit the measurement of individual components, but instead must be measured as a whole. It should be further noted that the procedures described herein are still subject to further revision as more experience is gained from their application. Depending on the design of the NVGs (folded optics, off-set input/output axes, eyepiece combiners, etc.) some of the procedures are more difficult to apply than others.

Prior to evaluation of any NVG it is critical that the NVG be properly prepared to insure fair and accurate measurement of its characteristics. The optics should be carefully cleaned and adjusted. If the NVG has adjustable objective lenses and/or eyepiece lenses, these need to be set for infinity and zero diopters respectively. For measurements involving brightness and brightness gain the NVG should have fresh batteries to insure optimum results. During testing the NVGs should be checked periodically to make sure the optics are still clean (no fingerprints!).

BRIGHTNESS AND BRIGHTNESS GAIN

1.1 Introduction

Brightness and brightness gain are measurements of the luminance output of NVGs as a function of luminous input. In strictest terms, these parameters should really be called *luminance* and *luminance gain*, because the measurements conducted for this part of the evaluation are photometric. Brightness implies visual perception, an unmeasurable quantity. However, since brightness and brightness gain have been the terms used traditionally, we will conform to this convention.

Night vision goggles cannot work in complete darkness. They are essentially amplifiers of visible and near-infrared radiation. The measurement of brightness and brightness gain give some indication of how well a night vision system amplifies natural ambient light. Brightness is a measurement of the limit imposed on the maximum goggle output by the automatic gain control and gives an indication of how easily a user could see the intensified image of a well lighted area. The NVG's brightness gain is the ratio of the output luminance from the goggle to the input luminance to the goggle.

NVGs have an unusual spectral sensitivity, which makes the concept of brightness gain difficult to define. Gain involves a ratio of similar quantities, in this case, luminances, which are only defined for the spectral sensitivity of the human eye. Unfortunately, the eye and the NVG's image intensifier tube are sensitive to slightly different regions of the spectrum. Problems arise because the NVGs can "see" sources which are undetectable by the human eye and, therefore, have zero luminance. This allows a condition in which infinite gain could be calculated. For example, a source emitting light with a wavelength of 900 nanometers would have zero luminance because the eye is relatively insensitive to infrared radiation. But when viewed through an NVG, which is very sensitive to this wavelength, the system will produce a non-zero output luminance. A non-zero output luminance divided by a zero input luminance will produce an infinite value for gain.

To overcome this problem, it is necessary to define a specific spectral distribution for an input light source which emits radiation in both the visible and near infrared spectral region. The visible portion of the emitted radiation provides a measurable, non-zero input luminance. A light source simulating a 2856 degree Kelvin (K) black body

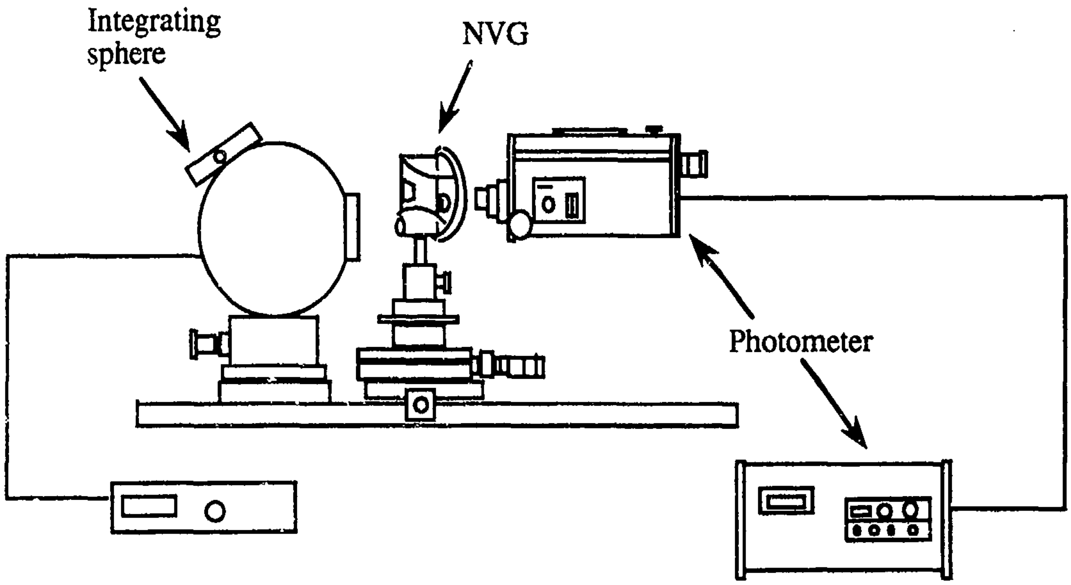

Figure 1. Test setup for the brightness gain procedure.

radiator was selected because it is a standard lamp, is easily approximated using halogen bulbs, and is specified as a light source for testing image intensifier tubes in the ANVIS image intensifier assembly specification (6).

1.2 Approach

The input light source may be any device that approximates the spectral distribution of a 2856 K blackbody radiator, emits very uniform luminance across its field, and can fill the entire field of view (FOV) of the NVG under test. Either an integrating sphere or a uniform, wide field of view collimator is a good choice.

The equipment arrangement for the brightness and brightness gain measurement using an integrating sphere is shown in Figure 1. The arrangement for use with a collimator is the same, except the collimator replaces the sphere. This procedure requires a light source with a desired luminance range of 10^{-6} footlamberts (fL) to 0.02 fL and a photometer which must be sensitive down to 10^{-5} fL.

Controlling the output from the light source while maintaining the correct color temperature and uniformity of its luminance across the output field is essential for accurate results. This is best accomplished by using a variable slit or aperture between the bulb and the integrating chamber of the light source. Altering the bulb voltage to change the output level will alter the source's color temperature. All these factors must be carefully considered when choosing a light source because of their significant impact on the results.

The photometer used was modified with a 7 mm limiting aperture over its objective lens for this procedure only. The 7 mm aperture was chosen because it is the same diameter as the widest eye pupil in low luminance conditions. Its presence required the photometer to be recalibrated to compensate for the reduced light gathering capacity. However, the aperture was necessary to ensure accurate luminance readings from NVGs with exit pupil forming optical systems. If the photometer objective lens is larger than the NVG exit pupil, erroneously low readings will be obtained.

The photometer is positioned in front of the light source to check its calibration and ensure that the emitted luminance values are correct for the corresponding aperture settings. The NVG to be tested is positioned with the objective lens of one ocular as close to the light source as possible. The limiting aperture of the photometer is placed at the expected eye position of the NVG and pointed toward the approximate center of the NVG's field of view. The measuring field of view of the photometer should be no greater than 2° as stated in the ANVIS image intensifier assembly specification.

Once all components have been positioned, the light source is adjusted to produce an input to the NVG objective lens of 10^{-5} fL. The output luminance from the NVG is measured by the photometer and recorded. The aperture in the light source is then adjusted to produce a higher luminance and the photometer reading is again recorded. This is repeated until the lamp reaches its maximum luminance capability, 0.02 fL.

The step sizes between luminance levels should be spaced more closely at lower levels and further apart at higher levels. Changing values by a factor of two is a good compromise between limiting the procedure to a reasonable number of data points and providing sufficiently fine interval spacing so as not to miss any interesting effects (see Table 1).

1.3 Results

The results from this measurement procedure can be displayed in tabular form (see Table 1) with three columns of data: input luminance, output luminance, and the ratio of output to input labeled brightness gain. The raw data can also be displayed in

Table 1. Example of brightness gain tabular data.

Input luminance (fL)	Output luminance (fL)	Brightness gain (unitless)
$1.10X10^{-5}$	0.0200	1820
$2.30X10^{-5}$	0.0400	1740
$4.60X10^{-5}$	0.0800	1740
$9.20X10^{-5}$	0.170	1850
$1.84X10^{-4}$	0.350	1900
$3.67X10^{-4}$	0.720	1960
$7.34X10^{-4}$	1.23	1680
$1.47X10^{-3}$	1.24	849
$2.94X10^{-3}$	1.25	425
$5.88X10^{-3}$	1.26	214
$1.18X10^{-2}$	1.27	107
$2.35X10^{-2}$	1.27	54.0

graphical form (Figure 2) with output luminance plotted against input luminance. The maximum output luminance value obtained is then recorded as the maximum brightness of the NVG.

As noted from Table 1, brightness gain is a unitless fraction describing the ratio of light out of the system to light into the system at specific input light levels, while brightness is the luminance output at the same input light levels, expressed in ft-Lamberts. Brightness gain is determined by dividing the output luminance by the input luminance (column three in Table 1). This can also be graphed as the brightness gain as a function of input luminance (Figure 3). The gain at $3.67 * 10^{-4}$ fL input is recorded as the brightness gain. This value is somewhat arbitrary and was chosen because most NVGs, tested in this fashion, reach their maximum brightness gain value at or near this luminance input level.

1.4 Comments

It must be kept in mind that the results are for a specific standard lamp color temperature. When spectral distribution or color temperature of the light source is different, different results will be obtained.

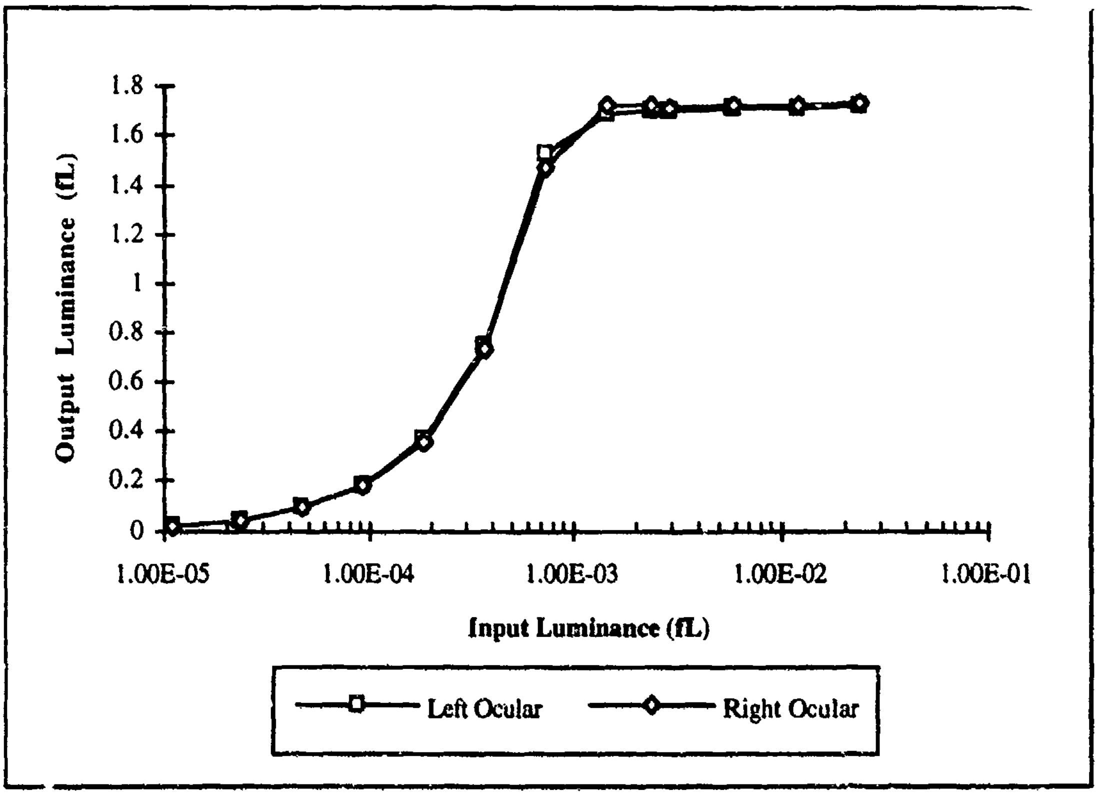

Figure 2. Output luminance vs. input luminance

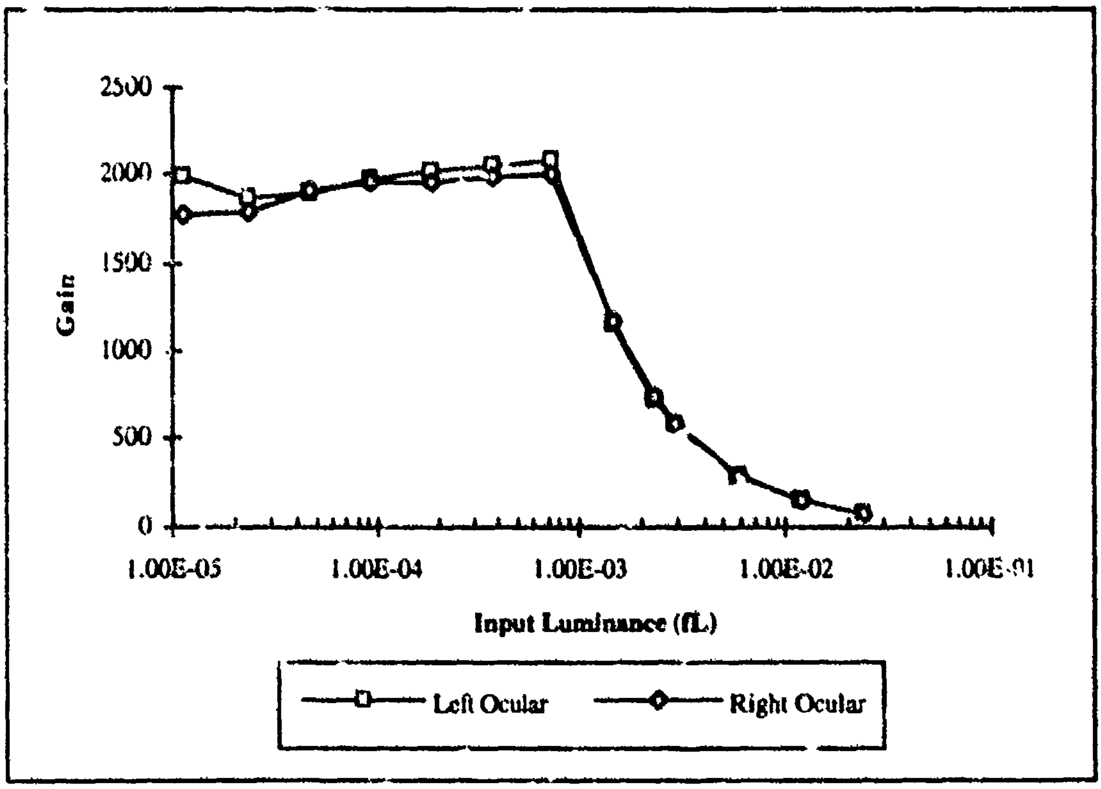

Figure 3. Brightness gain vs. input luminance

The brightness gain graph, such as Figure 3, provides some information on how well the NVG amplifies light. However, the luminance output curve shown in Figure 2, which is also obtained from this procedure, provides an indication of how much light the observer has to see in the NVG image. Since visual acuity of the observer varies considerably with light level (4) the latter curve provides some information as to the visual capacity of the observer to extract key information from the scene as displayed by the NVG.

Table 1 and Figures 2, and 3 indicate that brightness and brightness gain are affected by the level of input luminance, although they are typically only recorded at specific values, brightness at its maximum value and brightness gain at an input luminance of about $3.67 * 10^{-4}$ fL. This can be misleading, since the NVGs are often operated at light levels other than those at which these maximum brightness and brightness gain values occur.

All NVGs are equipped with an automatic gain control to protect the goggles from damage. The graphs of brightness and brightness gain are heavily influenced by the gain control circuit. It limits the maximum brightness leaving an NVG and determines at what input light level the slope of the brightness and brightness gain curves begin to change.

This procedure requires that the light source fills the full field of view of the NVG. If this is not the case, it is possible to obtain drastically different brightness and brightness gain results. The automatic gain control limits the total current flow within the image intensifier tube. The same current may be generated from a considerable amount of light on a small area of the NVG or by a small amount of light on a large area. In the first case, the output luminance will be much higher than in the latter. Figure 4 shows several brightness curves that were generated by filling up different fractions of the field of view. Note that, as the area of the light source is reduced at the input, much higher maximum output luminances are obtained.

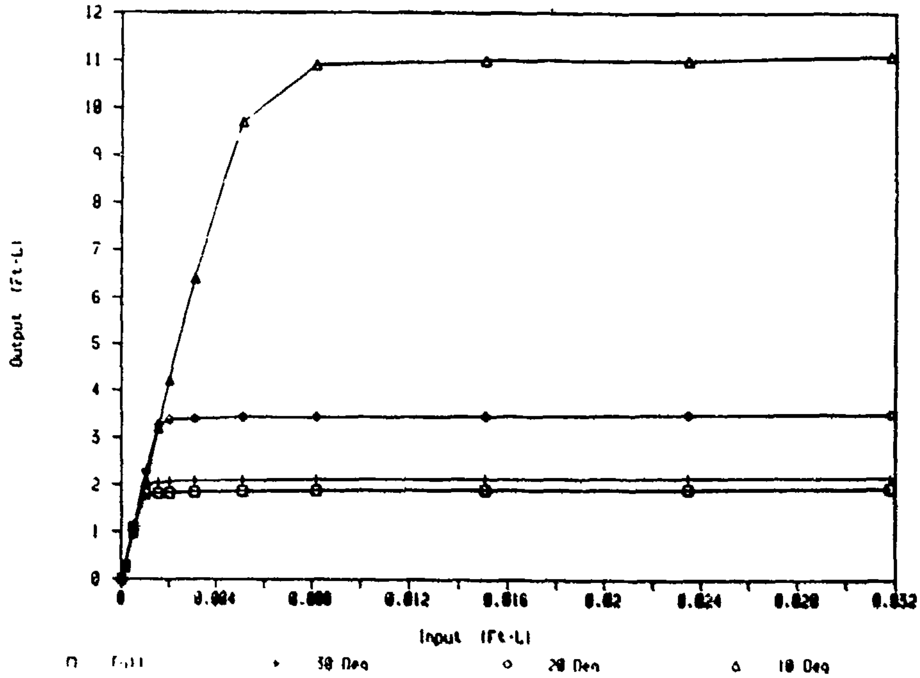

Figure 4. Output luminance vs. input luminance for various illuminated fields of view.

GEOMETRIC IMAGE PARAMETERS

2.1 Introduction

The four parameters addressed in this section: 1) distortion, 2) image rotation, 3) magnification, and 4) optical axis misalignment, all deal with geometric aspects of the image produced by the night vision goggles. Thus, a single measurement procedure was developed to capture all four parameters simultaneously.

Distortion, the non-linear mapping of the outside scene to the output image plane, is probably the most difficult parameter to characterize, because there are several types of distortion that may occur in NVGs. The optical system may cause barrel or pincushion distortion. The fiber optic twist, which is used in many, but not all NVG designs, may produce both shear effects and "S" distortion. Of all of these, the procedure herein described is primarily directed at characterizing the "S" distortion, although evidence of shear, barrel, and pincushion distortion may also be detected. "S" distortion originates in the fiber optic plug, which is used to invert the image intensifier's output image, when it is manufactured by heating and twisting approximately 180°. The "S" distortion is so named because there is usually a small amount of residual effect due to the twist that produces an "S" shaped curve from a straight line input. The more the output image departs from a straight line, the worse the distortion.

Another problem encountered with NVGs is image rotation. For NVGs incorporating fiber optics, the fiber optic plug may be twisted somewhat more or less than 180°, resulting in the output image being rotated compared to either the input image or the other ocular. This effect may also be exaggerated by inaccurate alignment of the mirrors in a folded optical system.

Magnification is another geometric image parameter that must be addressed. Most NVGs are designed to have unity magnification. However, if there is a mismatch between the objective lens and the eyepiece lens, it is possible to have a small amount of magnification (or minification). The procedure can determine the amount of image size increase or decrease produced by the NVG lens and image intensifier tube system compared to the unity magnification of the unaided eye.

An additional problem area is optical axis alignment. Since the combination of objective lenses, folding optics, image intensifier and eyepiece lenses is relatively complex, it is possible to have a mismatch between the input optical axis and the output optical axis. Thus, objects that are at a particular point in object space may appear to be at a different point when viewed with NVGs. The parameter measured is the relative angular difference between the objective lens optical axis and the eye lens optical axis for NVGs.

2.2 Approach

The equipment required for this measurement includes a rotary table, on which to mount the NVGs, a collimator with single small point image, a small, CCD array video camera, and a video monitor. It is also necessary to have digital calipers to accurately measure distance on the face of the video monitor. Figure 5 depicts the arrangement of the equipment for this measurement procedure.

To conduct this measurement correctly, the CCD camera must be fitted with a comparatively long focal length lens, on the order of 100 mm to 120 mm. This makes the camera more sensitive to optical defect phenomena by creating a larger spot size and

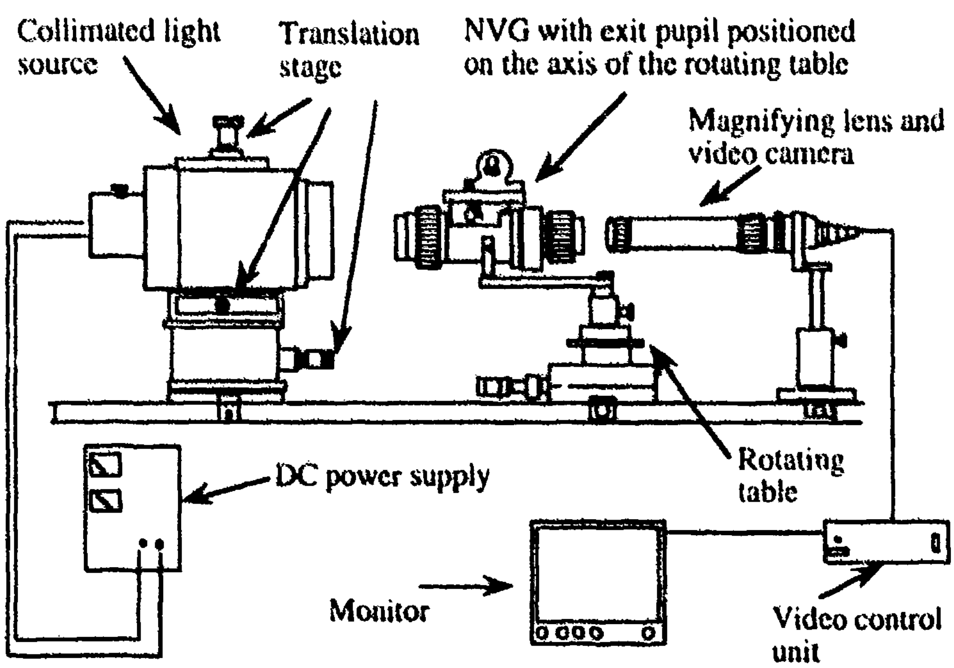

Figure 5. Test setup for the distortion procedure.

larger movements on the video monitor which are easier to measure accurately. The camera field of view must also be known in order to convert linear distance on the monitor into units of angular deviation.

The video camera is adjusted in front of the collimator, without the NVG in the system, until the small point image appears in the center of the video monitor. This aligns the optical axis of the video camera with the collimator. The NVG is then mounted on the rotary table between the video camera and the collimator such that the axis of rotation of the table is directly below the eye position of the NVG. The camera is then adjusted to position its objective lens directly over the table's axis of rotation. The spot of light within the collimator should now be visible on the monitor when viewed through the NVG. If the spot is no longer in the center of the video monitor, then the input and output optical axes of the NVG are not in alignment. By knowing the angular field of view of the video camera and the linear vertical and horizontal distance that the spot of light has moved from the center of the video monitor, the elevation (vertical) and azimuth (horizontal) angular misalignment value can be calculated.

After the on-axis misalignment has been recorded, the rotary table is then turned both clockwise and counter-clockwise, until a line across the full field of view has been scanned. At each field angle the vertical and horizontal position of the spot of light on the video monitor is measured and recorded.

2.3 Results

At the end of the above procedure, one has a table of results that consists of three columns: 1) horizontal angular position, 2) vertical angular offset, and 3) horizontal angular offset. Table 2 shows results for a typical NVG. These data points can be graphed and analyzed in different ways to obtain information on each of the four geometric parameters discussed. To determine the presence of unusual distortion phenomena, the vertical and horizontal offset data was plotted against angular position in Figure 6. Curved, symmetric edges of the graph indicate barrel or pincushion distortion. Jagged discontinuities indicate areas of shear effects.

Optical Axes Misalignment Analysis

The misalignment from the input to the output optical axis can be determined from the zero position angular offset. The offset in both vertical and horizontal

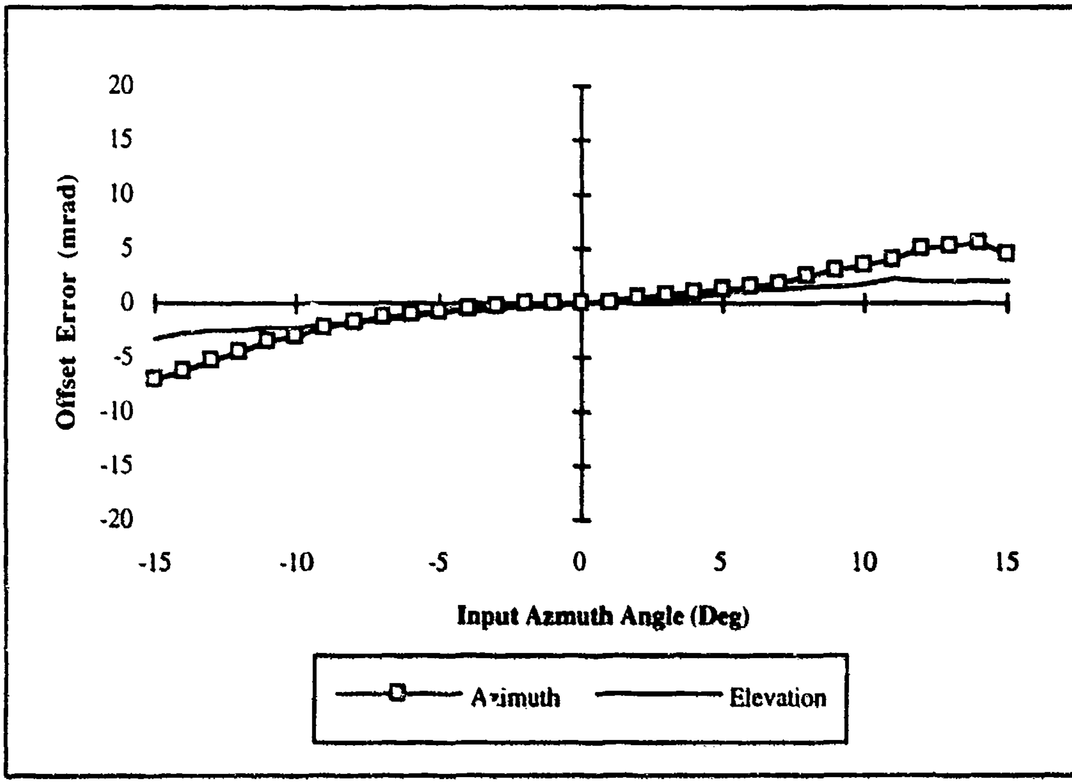

Figure 6. Distortion: offset data plotted vs. angular position.

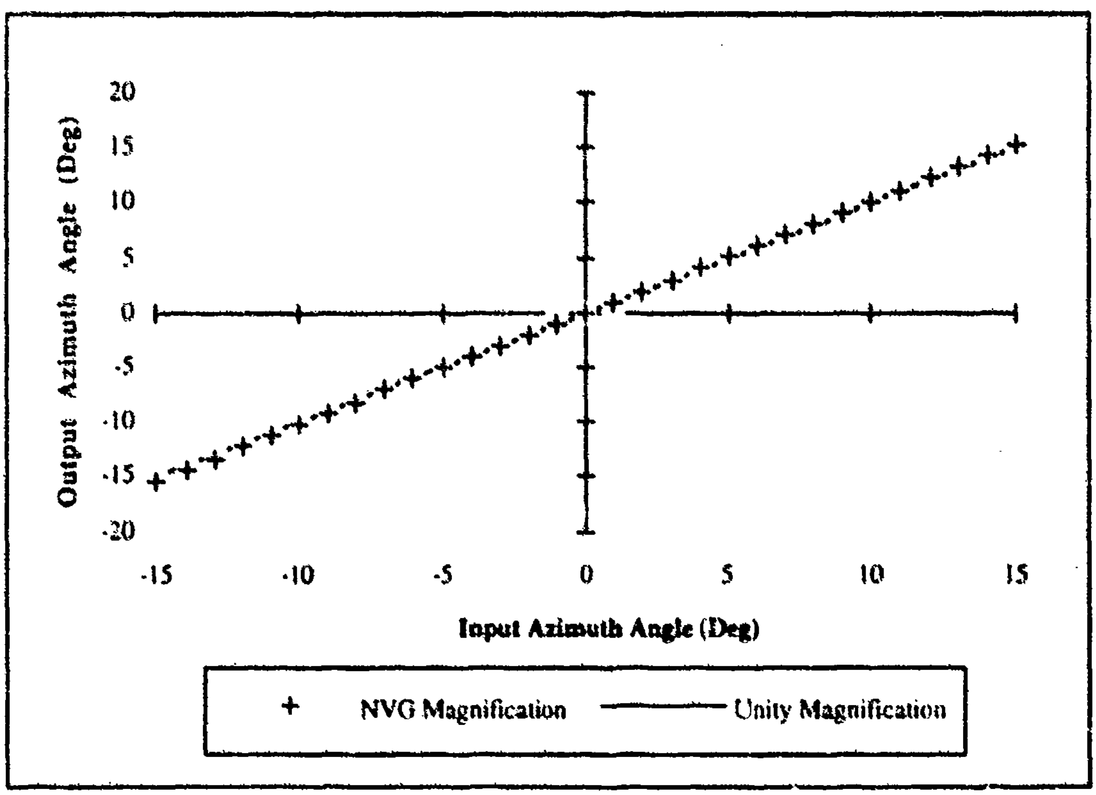

Figure 7. Magnification: output azimuth angle vs. input azimuth angle.

Table 2. Geometric measurement procedure tabular data.

Horizontal Position degrees	Vertical Offset milliradians	Horizontal Offset milliradians
-15	-6.977	-3.189
-14	-6.284	-2.903
-13	-5.365	-2.549
-12	-4.625	-2.580
-11	-3.575	-2.331
-10	-3.170	-2.357
-9	-2.370	-2.057
-8	-1.775	-1.686
-7	-1.324	-1.643
-6	-1.025	-1.177
-5	-0.765	-0.917
-4	-0.559	-0.700
-3	-0.339	-0.426
-2	-0.165	-0.286
-1	-0.015	-0.197
0	0.0	0.0
1	0.068	0.166
2	0.570	0.354
3	0.823	0.466
4	0.904	0.523
5	1.134	0.889
6	1.466	1.174
7	1.800	1.143
8	2.362	1.383
9	2.863	1.394
10	3.491	1.783
11	3.922	2.154
12	4.929	1.866
13	5.137	1.880
14	5.395	1.871
15	4.559	2.040

dimensions from the zero degree field angle position in Table 2 is the amount of vertical and horizontal misalignment. A single quantity representing the angular misalignment between the two viewing axes, O, of the NVG is also determined by taking the square root of the sum of the squares of the vertical and horizontal offset (equation 2.1),

$$O=\sqrt{X^2+Y^2} \tag{2.1}$$

where Y is the vertical angular offset in degrees and X is the horizontal angular offset in degrees. This measurement can be recorded in milliradians, degrees, or minutes of arc.

Magnification Analysis

If magnification other than unity magnification is present in the system, then the horizontal angular offset would increase at a uniform rate with respect to the horizontal field angle as the horizontal angular scan is produced. This can be graphed as the horizontal field angle plus horizontal angular offset versus actual input field angle. Since there is also typically some distortion present, this line may not be perfectly straight. To circumvent this problem, a linear, least-squares fit is made to the data to provide a best fit line with slope and intercept. The slope of the least-squares fit straight line is the magnification of the system. A reference slope of one, representing unity magnification, is also graphed for comparison with the measured value (see Figure 7). Note that this analysis can easily be modified to examine data from a smaller portion of the total system. If there is significant distortion at the outer edges, for example, the data reduction can be restricted to the central 80% of the field of view.

Image Rotation Analysis

Image rotation analysis is very similar to that done for the magnification, except the vertical (elevation) angular offset is graphed as a function of horizontal field angle. Again, a linear, least-squares fit line is computed and graphed along with the data (see Figure 8). The amount of image rotation, Θ, is the arctangent of the slope, $\pm m$, of the best fit line (see Equation 2.2).

$$\theta=\tan^{-1}(\pm m) \tag{2.2}$$

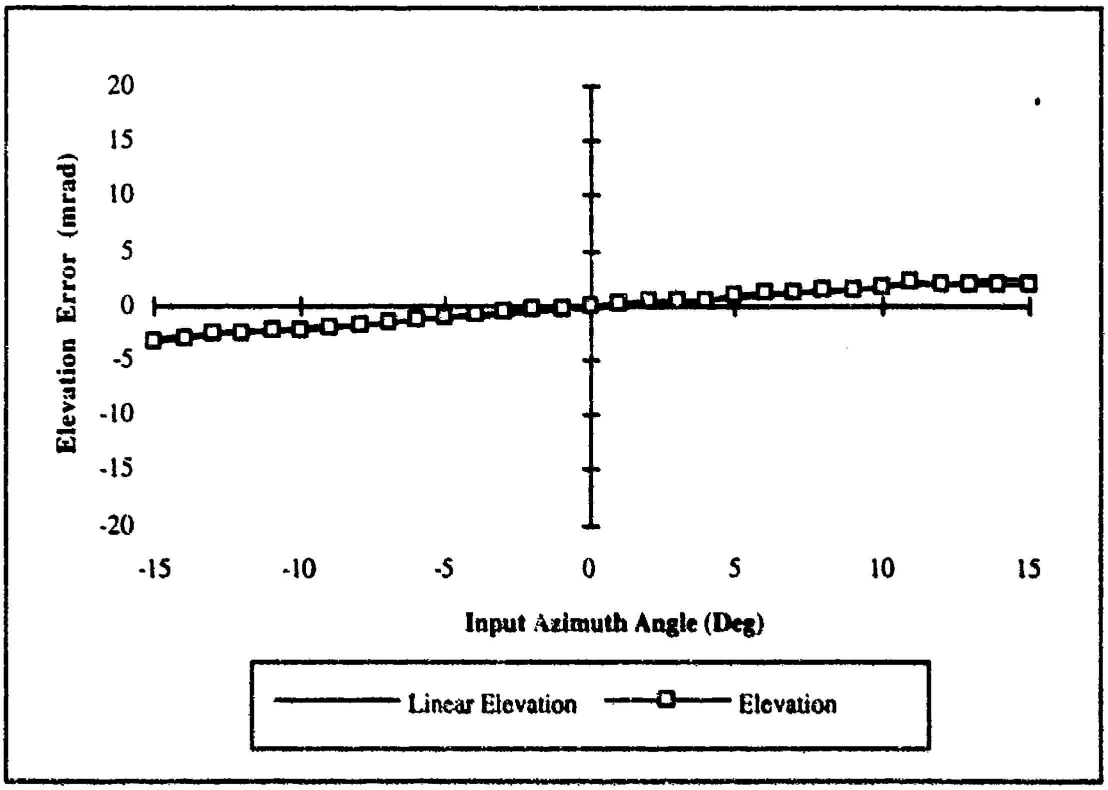

Figure 8. Image rotation: vertical angular offset vs. input azimuth angle.

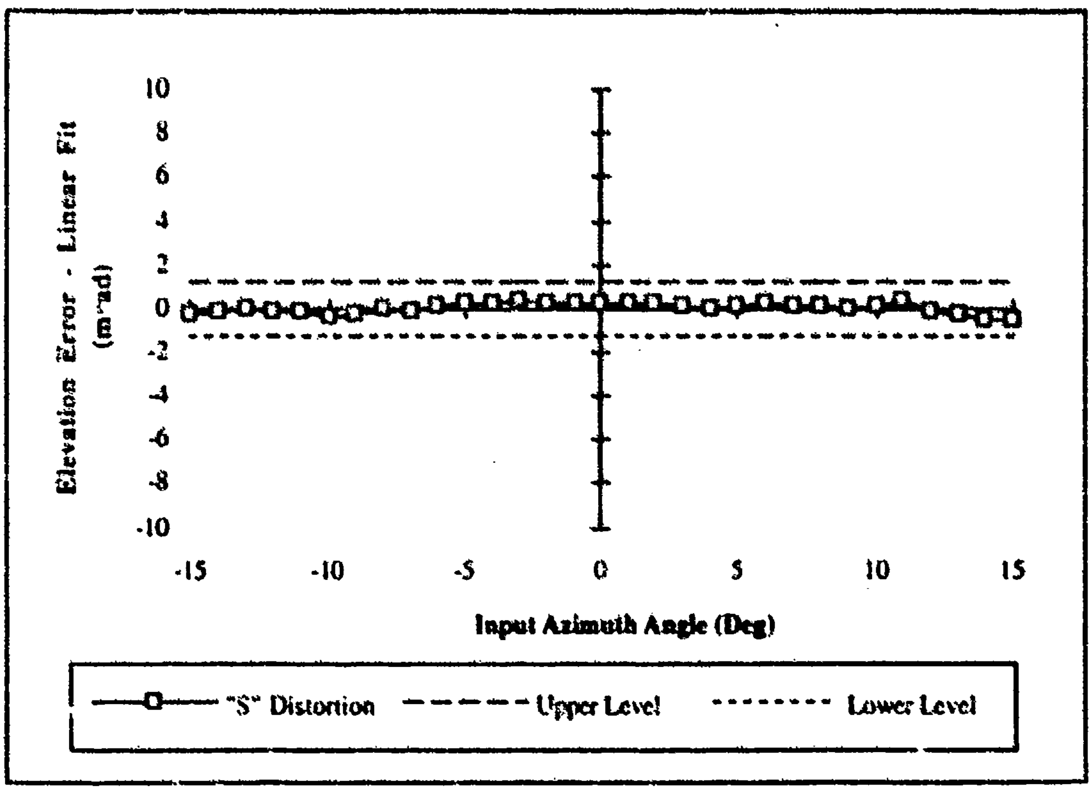

Figure 9. "S" Distortion: vertical offset minus rotation curve fit error vs. input azimuth angle.

Distortion Analysis

The "S" distortion can be displayed on the same graph as image rotation. However, to obtain a clearer picture of the "S" distortion by itself, the linear best fit curve for image rotation can be subtracted from the vertical angular offset data. This difference can then be graphed against horizontal field angle. Current specifications require that the "S" pattern fit between two horizontal lines, such as those on the graph in Figure 9, that are spaced ±1.22 milliradians from the origin, corresponding to a ±30 microns maximum allowed by the ANVIS image intensifier assembly specification. This value is for the fiber optic plug only and comes from the ANVIS image intensifier assembly specification. It can, however, be generalized to the NVG as a whole. For a quantitative measure of the "S" distortion, the maximum value is subtracted from the minimum value to obtain the peak to valley amplitude of the curve.

2.4 Comments

The angular offset in both the vertical and horizontal dimensions from the zero degree field position (Table 2) demonstrates the amount of vertical and horizontal optical axis misalignment. Ideally, the collimator output is used to define the optical axis of the video camera and the input optical axis of the NVG system. With exaggerated offset optical systems where the separation between the camera axis and the NVG input axis is greater than the collimator lens diameter, a slight modification of this procedure is needed. The measurement is then accomplished by translating the collimated light source from the eyepiece position to the objective lens position, measuring the change in position of the point light source on the video monitor.

The evaluator must be careful not to introduce tip or yaw of the collimator into the system as the collimator is translated. Doing so would destroy the axis reference with the video camera and render the results meaningless. Strong, precision machined mounts are required to prevent this.

Magnification other than unity magnification along the edges of the image is an indication of either pincushion or barrel distortion. These aberrations can be caused by either the relay or imaging optics, the fiber optics, or by some combination.

EXIT PUPIL SIZE (DIAMETER)

3.1 Introduction

NVG optics can be either non-pupil forming or pupil forming. The measurement of exit pupil size is a procedure performed on real pupil forming systems only. A pupil forming system, such as a telescope, has an area where the entire image can be seen as long as the eye is anywhere within it. However, as the eye begins to move out of the exit pupil the image first begins to dim and finally disappears when the eye entrance pupil is completely outside of this area (7). In pupil forming NVG optical systems, the exit pupil is the image of the aperture stop as viewed from image space.

3.2 Approach

The equipment arrangement for the exit pupil measurement using a collimator is shown in Figure 10. An integrating sphere can also be used, provided the NVG field of view is filled. This procedure requires a translational target stand with a mounted screen of thin diffusing material.

The objective lens of the NVG is placed close to the exit aperture of the collimator, ensuring the NVG's field of view is fully illuminated. The translation stage with the diffusing screen is then placed behind the NVG eyepiece. With the NVGs on and the room completely dark, the real image (circle of light with the smallest diameter) formed by the eyepiece is brought into focus on the diffuser by moving the translation stand toward or away from the NVG. The diameter of the image, or exit pupil diameter, is then measured with digital calipers and recorded. This procedure is repeated five times to obtain an average value.

3.3 Results

The results from this measurement procedure can be displayed in tabular form (see Table 3). Due to the subjectivity of the measurement, the data is statistically analyzed so that the confidence interval (C.I.) of the measurements can be determined.

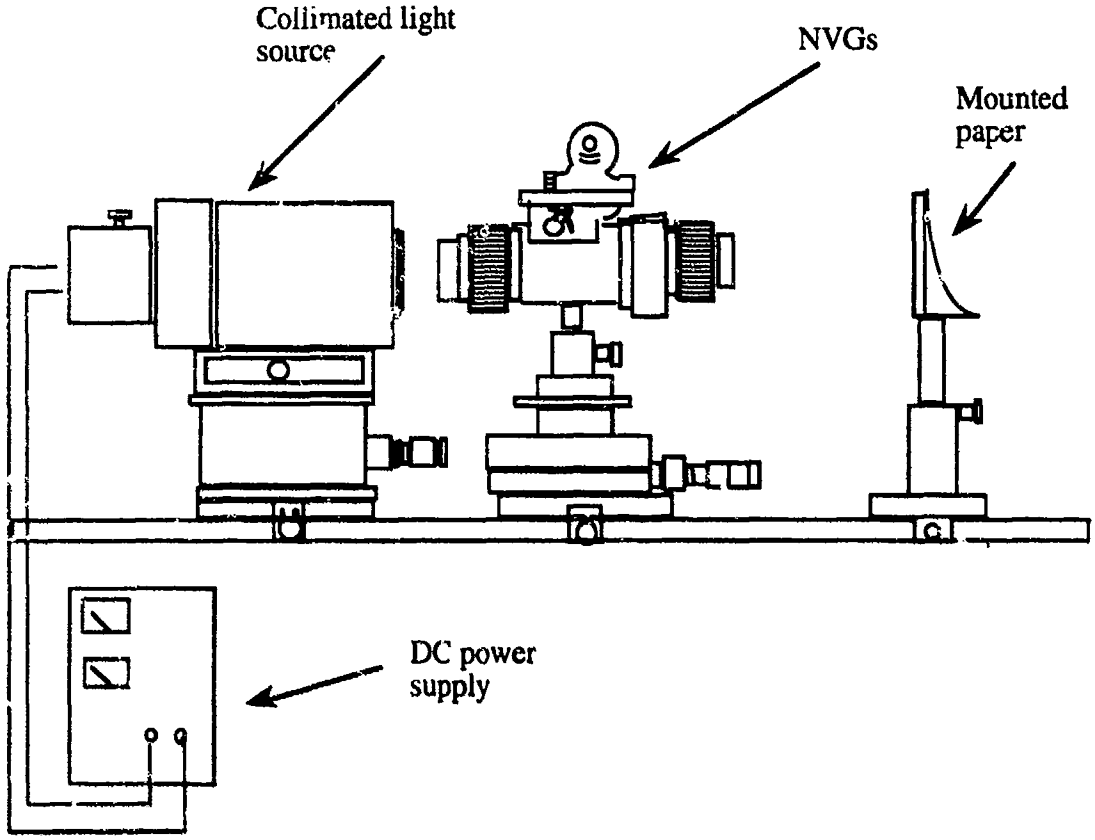

Figure 10. Test setup for the exit pupil diameter procedure.

Table 3. Example of exit pupil diameter tabular data.

Measurement Number	Exit Pupil Diameter (mm)
1	9.5
2	9.5
3	9.0
4	9.3
5	9.0
Average	9.26
Variance	0.25
95% C.I.	9.26 ± 0.35

3.4 Comments

It may be noted that different materials can be used for the screen. Anything that is translucent and scatters light relatively uniformly could be used Unfortunately, the thickness of the diffuser limits the precision of the measurement. When trying to determine the exact location of an image plane to a tenth of a millimeter, it becomes the limiting factor. Therefore, a thin diffusing material, such as cellophane tape, produces the best results.

EYE RELIEF

4.1 Introduction

As already noted, some NVGs are pupil forming and some are non-pupil forming systems. The procedure for measuring eye relief changes somewhat depending on which of the two types is being tested, but the basic definition remains the same. In this report, eye relief is defined as the physical distance separating the last optical surface of the NVG eyepiece from the front surface of the eye, the cornea.

A non-pupil forming system is similar to a simple magnifying lens in that, as you move your eye away from it, the edge of the field may be cut off (vignetted) (7). Therefore, the maximum eye relief for such a system is defined as the maximum distance between the last optical element in the NVG eyepiece and the cornea, such that the NVG user can still see the system's full, unvignetted field of view, minus 3 mm. For a pupil forming NVG, eye relief is the distance from the NVG's last optical element and the plane of the exit pupil minus 3 mm. Since the entrance pupil of the human eye must fall at the system's exit pupil for ideal viewing, the distance from the cornea to the eye's entrance pupil must be subtracted.

These definitions do not conform to the ANVIS specification for eye relief, which has more to do with the diameter of the eyepiece lenses than the actual distance separating the NVG and the eye. The results from this procedure give a real distance which is useful in determining things such as system compatibility with protective equipment and eye glasses.

4.2 Approach

Figure 11 shows the equipment arrangement for the eye relief measurement. The procedure to measure non-exit pupil forming NVGs requires a collimator with a square grid insert with numbered vertical and horizontal axes to identify position, a micro CCD array camera with a 5 mm aperture, and a video monitor

The CCD video camera's field of view must exceed the FOV of the goggle under test. To achieve this, a short focal length lens is used to image the goggle output onto the CCD array. In this case, a lens with a focal length of 8.9 mm was used. As mentioned

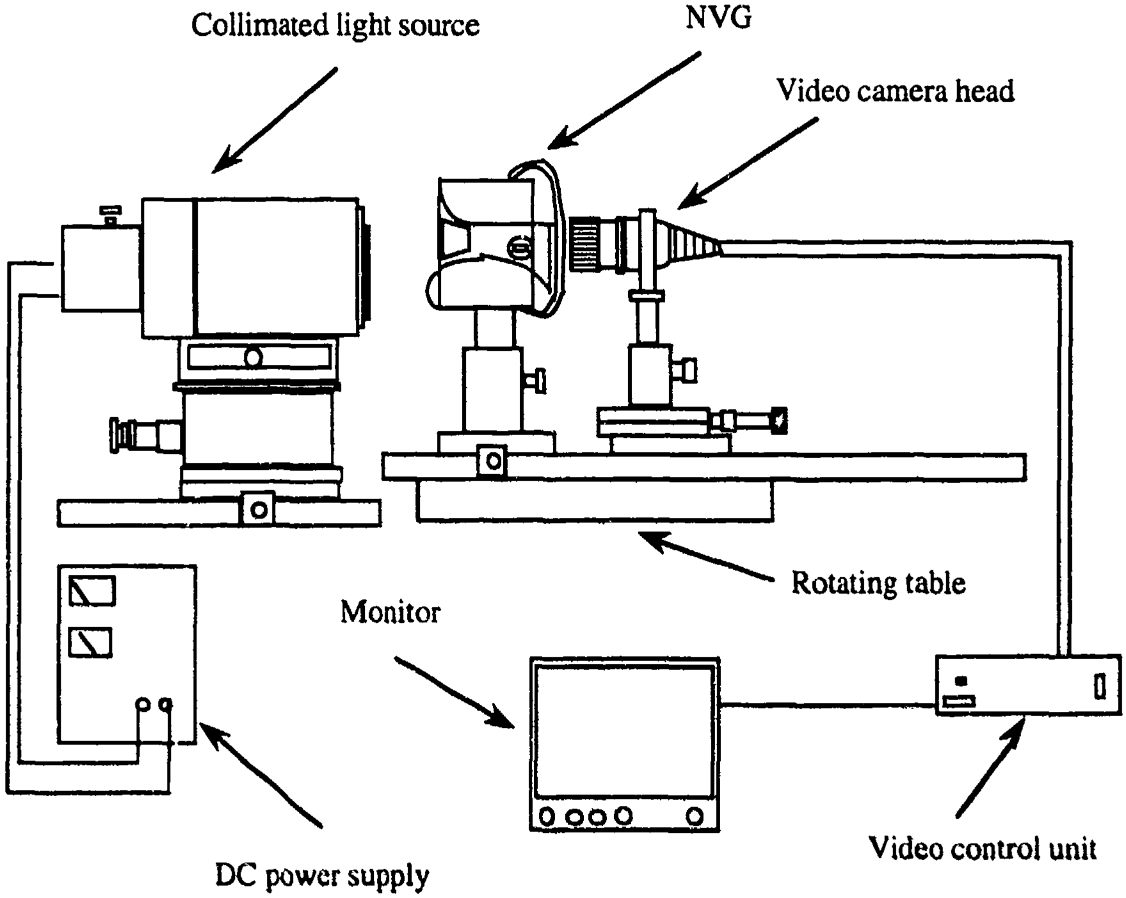

Figure 11. Test setup for the eye relief procedure

earlier, the ideal aperture size for night vision applications to simulate the human eye pupil is 7 mm. Due to equipment restrictions, a 5 mm aperture is used in conjunction with the video camera. This has only a marginal affect on the results.

The video camera is adjusted in front of the collimator without an NVG in the system, such that the origin of the grid pattern appears in the center of the video monitor. This will align the optical axis of the collimator with that of the video camera. The NVG is then mounted between the collimator and the video camera such that the entire FOV is filled with the grid image. In this procedure, both the NVG and the collimator remain stationary while the miniature video camera is translated along the optical axis. Then the video camera and translational stage are positioned such that the camera lens is almost touching the surface of the NVG eye lens. With the room lights turned off and the goggle turned on, the grid pattern should be visible on the monitor as viewed through the NVG. The location of the micropositioner is then recorded as the initial value, x_i. The camera is then moved away from the NVG eyepiece lens until vignetting occurs. The micropositioner location is then recorded as a final value, x_f. This procedure is repeated five times for each ocular to achieve an average value.

Eye relief measurements on exit pupil forming systems follow a similar procedure but require slightly different equipment. The CCD camera is replaced by a strip of thin diffusing material. Setup remains the same except the square grid insert for the collimator becomes optional.

With the goggles positioned in front of the collimator, the thin diffusing screen is placed in contact with the NVG eyepiece lens and its initial position is read from the translational stage and recorded as x_i. Like the procedure for non-exit pupil forming systems, the diffuser is moved away until the intensified image emerging from the goggles reaches its smallest diameter, or achieves best focus if the square grid insert is used. Both should yield equivalent results. The position of the stage is then recorded as x_f. Like the procedure for non-exit pupil forming systems, five measurements are taken on each ocular to calculate an average value.

4.3 Results

At the end of the measurement procedure, the eye relief can be calculated using the following equations. It is often helpful to display the raw data in a table before making the necessary calculations (see Table 4). For non-exit pupil forming systems, eye relief, $E\,R$, is calculated with Equation 4.1

Table 4. Example of eye relief tabular data

Measurement Number	Eye Relief (mm)
1	21.2
2	20.9
3	19.9
4	20.5
5	21.1
Average	20.7
Variance	0.53
95% C.I.	20.7 ± 0.74

$$ER = (x_f - x_i) + pp - 3mm \tag{4.1}$$

where *pp* is the distance from the vertex of the lens to the first principal plane of the video camera and 3 mm is the distance from the cornea to the entrance pupil of the eye.

The eye relief calculation for exit pupil forming NVGs is conducted with Equation 4.2

$$ER = (x_f - x_i) - 3mm \tag{4.2}$$

Due to the inherent subjectivity in the procedure, the data is statistically analyzed so that the confidence interval (C.I.) of the measurements can be determined.

4.4 Comments

For proper results, the micro CCD camera must provide a field of view greater than that of the NVG. If this is not the case, longer eye relief measurements will be obtained because the camera will not see the goggle's field starting to collapse until its own field starts to collapse. Overfilling the goggle's field of view is also critical to obtain reliable measurements. Vignetting will go undetected unless the goggle objective lens is completely filled. This will also result in longer eye relief measurements.

Vignetting may not occur evenly throughout the entire field of view. Often, part of the field collapses followed by the remaining FOV. To account for this phenomenon, a grid target with divisions representing angular units was used. The skill of the evaluator also adds some uncertainty to this procedure.

When organizing a test sequence to evaluate night vision equipment, this parameter should be measured first. Several other goggle evaluation procedures mentioned in this report depend on knowledge of the proper eye position for the alignment of equipment and accurate results.

VISUAL ACUITY

5.1 Introduction

Resolution is the ability of an imaging system to reproduce an image in fine detail. This procedure is actually a measurement of the human dependent analog to resolution, visual acuity. The method described herein relies on a subjective observation, in which a test observer views a USAF 1951 tri-bar resolution test chart through the NVG and determines the smallest discernible pattern. The average limiting acuity of the system as seen by several observers can be extracted from this observation.

5.2 Approach

The equipment required for this procedure includes a collimator with an aperture larger in diameter than the NVG objective lens aperture and a positive 1951 USAF tri-bar resolution pattern, one that produces an image of dark bars on a white background, positioned at the collimator's focal plane. Three experienced observers with vision corrected to 20/20 visual acuity or better are needed. Figure 12 shows the arrangement of the equipment for this measurement procedure.

The NVG objective lens is aligned to look into the collimator and is focused on the 1951 tri-bar pattern such that a minimum of 50% of the intensified FOV is filled with the tri-bar pattern image in order to prevent degradation of the resolution due to high output luminances (see Figure 4). The input light level for this measurement is approximately equivalent to full moon, $2.35 * 10^{-2}$ fL from a 2856 K light source.

Once the initial conditions are met, an observer places his/her eye in the proper eye position of the NVG. The observer looks through one ocular and is then asked to determine the smallest horizontal and vertical elements of the 1951 tri-bar resolution chart they can resolve. This procedure is repeated for each ocular and each observer.

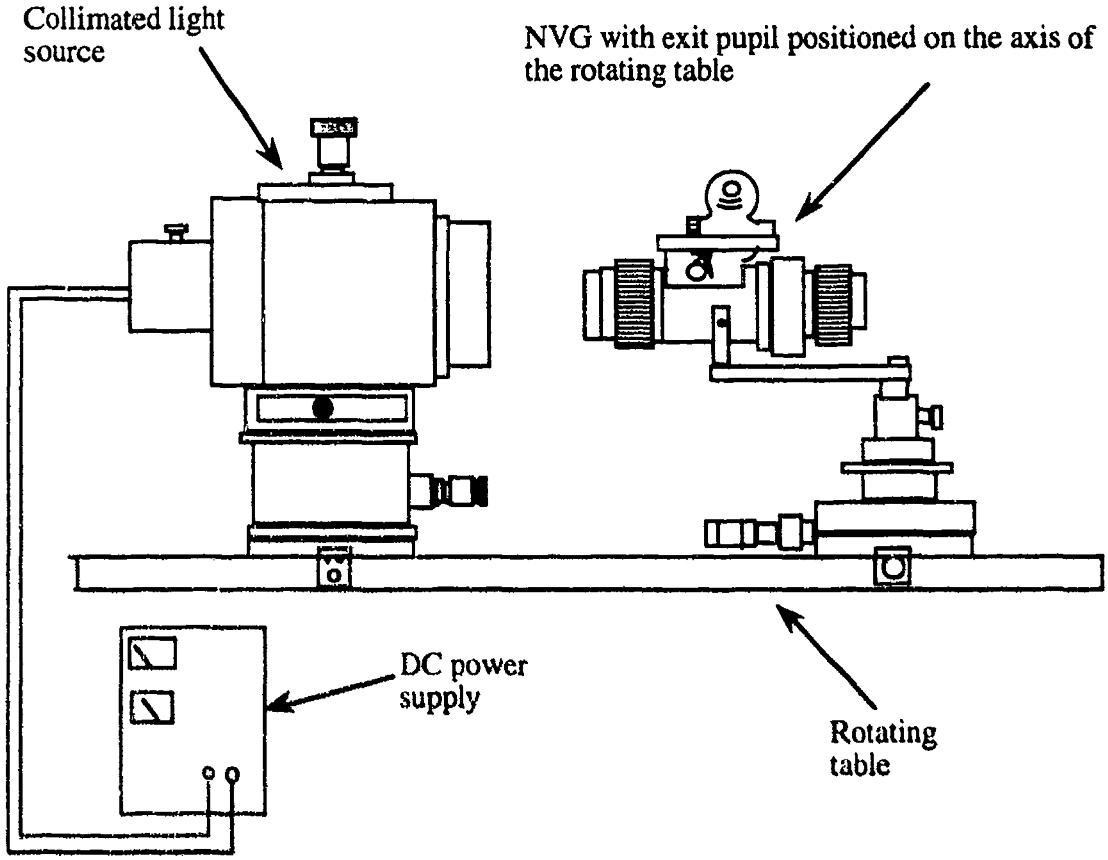

Figure 12. Test setup for the visual acuity procedure for center NVG FOV only.

5.3 Results

A table of raw data similar to Table 5 can be constructed. The smallest resolvable horizontal and vertical elements of the USAF tri-bar chart are then converted to either Snellen acuity or cycles per milliradian using Equations 5.1, 5.2, and 5.3.

Table 5. Example of resolution raw data, one ocular.

Observer	Group/ Element Horizontal	Group/ Element Vertical	Bar Width (mm) Horizontal	Bar Width (mm) Vertical
1	2/6	2/5	0.0710	0.0783
2	2/5	2/4	0.0783	0.0875
3	3/1	2/6	0.0625	0.0710

To convert group/element values to arc minutes use Equation 5.1,

$$\Theta = 60 \tan^{-1}\left(\frac{w}{fl}\right) \tag{5.1}$$

where θ is the subtended angle in arc minutes, fl is the focal length of the collimator in millimeters and w is the width of each bar of the chosen group/element in millimeters.

To calculate Snellen acuity use Equation 5.2,

$$X = \theta * 20 \tag{5.2}$$

where X is the denominator of the Snellen acuity ratio (i.e., $20/X$).

To convert from Snellen acuity to cycles per milliradian use Equation 5.3,

$$Y = 1.719 * 20/X \tag{5.3}$$

where Y is in units of cycles per milliradian and 1.719 is a conversion factor in cycles/milliradian.

The following example steps through each calculation. In this example, the observer's limiting resolution was recorded as group 2 element 5. The focal length of the collimator used was 100 mm and the bar width in the observed element was 0.0783 mm. First the subtended angle is calculated using Equation 5.4.

$$\Theta = 60 \tan^{-1}\left(\frac{0.0783}{100}\right) = 2.69\ \textit{arcminutes} \tag{5.4}$$

Knowing that the subtended angle is 2.69 arcminutes, Snellen acuity can be calculated with Equation 5.5.

$$X = 2.69 * 20 = 53.8 \tag{5.5}$$

So in this example, the observer resolved the target with 20/54 Snellen acuity. If the result is required to be reported in cycles/milliradian use Equation 5.6 for the conversion,

$$Y = 1.719 * 20/54 \quad (5.6)$$

which results in 0.64 cycles/milliradians.

After the raw data is collected, it is then converted to either Snellen acuity or cycles per milliradian and a table of final results can be constructed (see Table 6). The average acuity of the three observers is recorded as the resolution of the night vision goggle.

Table 6. Example of resolution tabular data, one ocular.

Observer	Horizontal Acuity	Vertical Acuity
1	20/48	20/54
2	20/54	20/60
3	20/43	20/48
Average Acuity	20/48.3	20/54

5.4 Comments

Once the collimator system has been fabricated and the focal length is known, it is recommended to make a conversion chart from milliradians to Snellen acuity for the USAF 1951 tri-bar chart. This will make data collection and reduction easier.

This is a subjective method, which relies on the experience of the 3 observers, so that an average may be calculated with some certainty. Note that both horizontal and vertical elements are recorded and analyzed to test the system for astigmatism.

RESOLUTION

6.1 Introduction

Measuring visual acuity can be a long and tedious process. The use of human subjects is a complication because they must be trained in the use of NVGs and must be relatively familiar with the system under test and the evaluation procedure. Because of this, the need for a quicker, more objective evaluation procedure appeared. In response, a photographic resolution procedure was developed based on the visual acuity test.

6.2 Approach

The equipment and test assembly are very similar to those used to measure visual acuity. A collimator with a negative 1951 USAF tri-bar resolution pattern, one that produces an image of white bars on a dark background, positioned in its focal plane is used as an image source and a 35 mm camera to record the resolution data.

The collimator must emit light which approximates the spectral distribution of a 2856 K blackbody radiator and emit full moon illumination, $2.35 * 10^{-2}$ fL. Its output must overfill the tested NVG's field of view and project an image of the 1951 USAF tri-bar chart that fills at least 50% of that goggle's field of view. This is required to avoid degradation of the resolution due to high output luminances. A negative 1951 tri-bar chart is used because it is easier to photograph through the goggles than the positive chart.

The camera used in this evaluation is a standard 35 mm camera with a 150 mm focal length lens well corrected for the third order aberrations and chromatic aberration. Like in other procedures mentioned in this report, the input aperture of the camera is limited to a 5 mm diameter to simulate the eye's entrance pupil at the correct light level. Photos are taken with Kodak 2415 technical pan film. Another equivalent film can also be used.

Once the collimator is properly adjusted, the goggles to be tested are aligned to the collimator's output. The goggles are then checked to see if the negative tri-bar chart image is damaging the image intensifier tube. As noted earlier in this report, small illuminated areas, such as the individual bars of the 1951 USAF chart, will cause greater localized gain than a fully illuminated goggle FOV because of the image intensifier tube's current control. This could leave minor burns on the NVG's phosphor screen. If the image seems to be overwhelming the goggle, the collimator's output luminance level is turned down slowly until the goggle is in no danger. This is to assure that the resolution photographs are taken at a high light level.

Once a non-damaging goggle output level is obtained, the camera is placed in the eye position of the NVG and the entire system is adjusted to achieve best focus through the goggle. Several photos are taken for different exposure times, ASA and F-stop settings. The photos are then developed and enlarged eight by ten inch prints are made. The best photo is selected for each ocular as its resolution data.

6.3 Results

The smallest resolvable group and element in both the horizontal and vertical

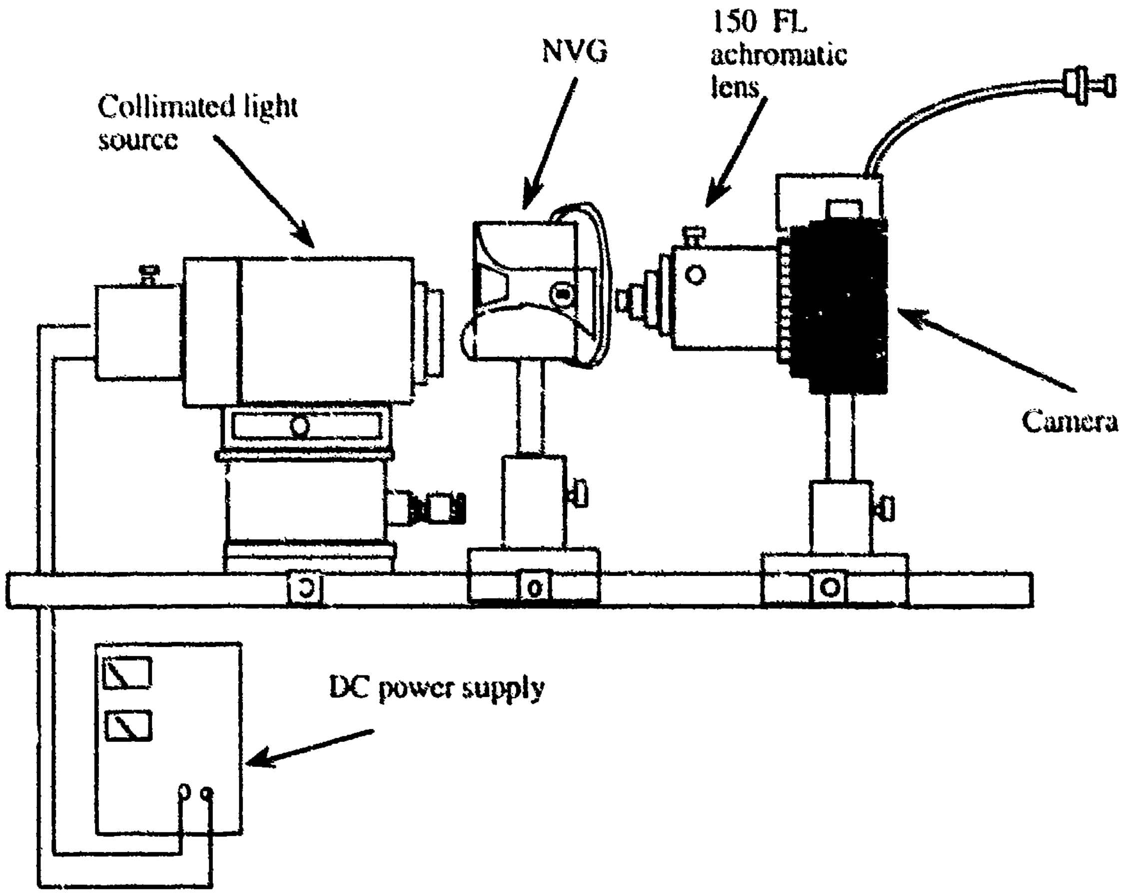

Figure 13. Equipment arrangement for the photographic resolution procedure.

direction are chosen from the photographs. Like the visual acuity data, this data can be converted to and recorded in arc minutes, cycles/milliradian, or Snellen acuity units using Equations 5.1 through 5.6.

6.4 Comments

The first time a camera, lens, and collimator are brought together to produce resolution photos, it would be wise to photograph the collimator output directly with the camera and lens. This creates a reference photograph and measures the limiting resolution of the resolution test system. The reference photo also records any astigmatism that might result from using poorly corrected optics.

This procedure is potentially hazardous to the NVG under evaluation because of the way the image intensifier tube processes physically small luminance sources. Excessively long periods of time due to alignment, focusing, or setting exposure times, during which the goggle is exposed to the collimator output are the main cause of problems. Damage could range from a slight phosphor blemish that fades with time to a serious non-removable burn. The risk of damage could be reduced by using a positive 1951 USAF tri-bar pattern in the collimator at the cost of losing some of the test system's ability to image it through the goggles.

VISUAL FIELD PARAMETERS

7.1 Introduction

The visual field parameters tested include intensified field of view, luminance uniformity, and modulation contrast. All of these parameters deal with data which is collected from a linear, photometric scan across the center of the NVG's visual field. A single measurement arrangement has been developed to capture information on all three parameters. Only small modifications in the procedure are required to collect the modulation contrast data.

The measurement of the intensified field of view gives an indication of the angular size of the real world scene the NVG can process and present to the user at any one particular time. This normally does not change much from ocular to ocular or from system to system of similar design. But, it can be an important factor when comparing different NVG designs.

Luminance uniformity measures the NVG output for uniform brightness throughout its entire visual field. A uniform luminance distribution implies that any photometric measurements taken in any part of the NVG field of view will result in similar measurements with only small deviations. However, previous tests on NVGs have demonstrated a common trend of variability in luminance across their field of view. Therefore, this is actually a test of luminance non-uniformity.

When an NVG is presented with a high contrast target, like an object with a bright side and a dark side separated by a sharp border, the high luminous output from the lighted areas tends to spill into the darker areas, making small dark targets surrounded by a bright background more difficult to see. Modulation contrast provides an indication of the maximum contrast an NVG can produce when viewing a 100% contrast target.

7.2 Approach

The equipment required for these measurements include a rotary table on which to mount the NVG, a photometer, a uniform 2856 K light source, and a strip chart recorder. In addition to this, a high contrast, split field target is used for the modulation contrast measurement only. Figure 14 depicts the arrangement of the equipment for this measurement procedure when using a collimated light source. For most of this procedure, either a collimator or an integrating sphere may be used, provided the NVG's full field of view is filled. But, the modulation contrast measurement must use the collimator as its light source. For tne results of this procedure to be truly meaningful, the split field target must be removed to infinity. The best way to accomplish this in the limited space of the laboratory is to place it in the focal plane of the collimator.

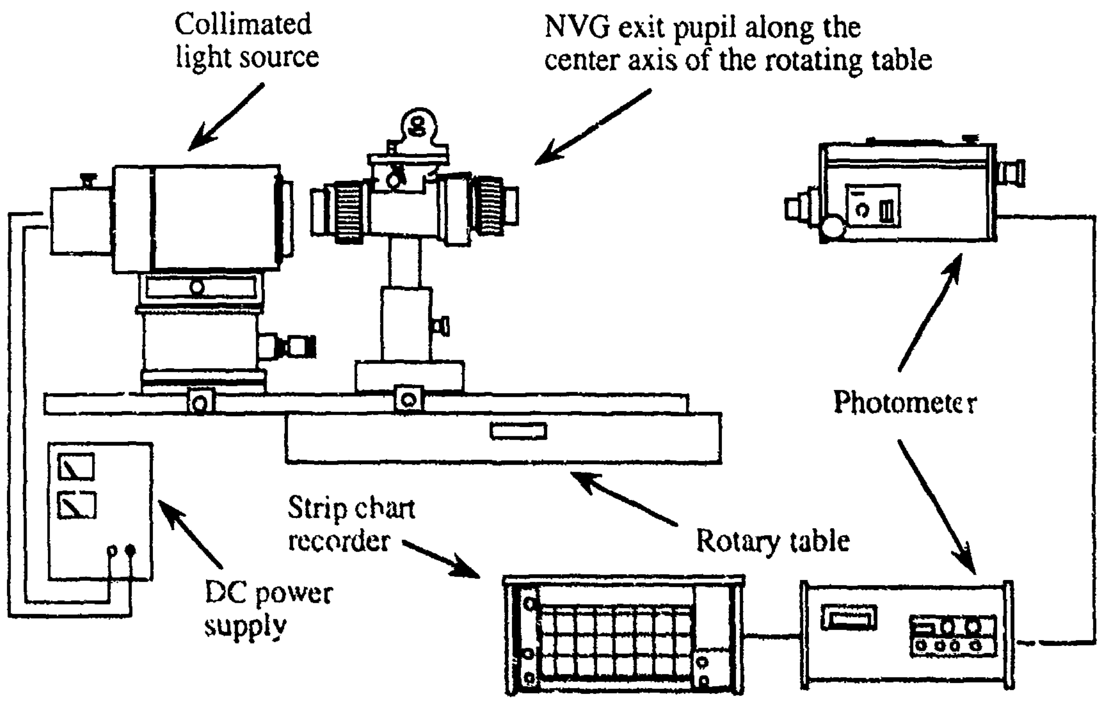

Figure 14. Test setup for the visual field measurements.

The NVG is mounted on the rotary table such that the goggle's proper eye position is directly over the table's axis. The collimator is then mounted on the rotary table such that it is close to and centered on the objective lens of the NVG being tested. The illumination from the light source is then adjusted so that it is bright enough to maximize the luminance output of the goggle intensifier tube. Full moon illumination is a good choice. The photometer is positioned so that it measures the luminance on the phosphorus screen of the image intensifier tube through the eyepiece of the NVG. A measuring FOV of less than 1/2° should be selected on the photometer.

In this procedure, the light source and NVG rotate together while the photometer remains stationary. The table is then rotated until the photometer is measuring a point just off the edge of the field of view of the NVG. The strip chart recorder is turned on and the rotary table is activated such that it sweeps through an angle greater than the field

Figure 15. Example of typical NVG field of view and luminance uniformity.

of view of the NVG. The resulting chart recorder trace appears in Figure 15.

The angular rate of the rotary table and the linear rate of the strip chart recorder need to be recorded and compared to generate a calibration factor, R_c, which will relate the strip chart recorder measurement to degrees. Measurements made in this fashion would be meaningless without it.

This procedure describes the measurement of field of view and luminance non-uniformity. These are just different reductions of the same plotted raw data. When measuring contrast modulation, the procedure is the same except a high contrast, split field target is placed at the image plane of the collimator. The resulting chart recorder plot has a somewhat different profile, as seen in Figure 16, than the plot for the field of view and luminance non-uniformity measurements.

7.3 Results

By the end of the procedure, at least two strip chart recorder plots per ocular have been generated. In the case of the intensified field of view and luminance uniformity, the

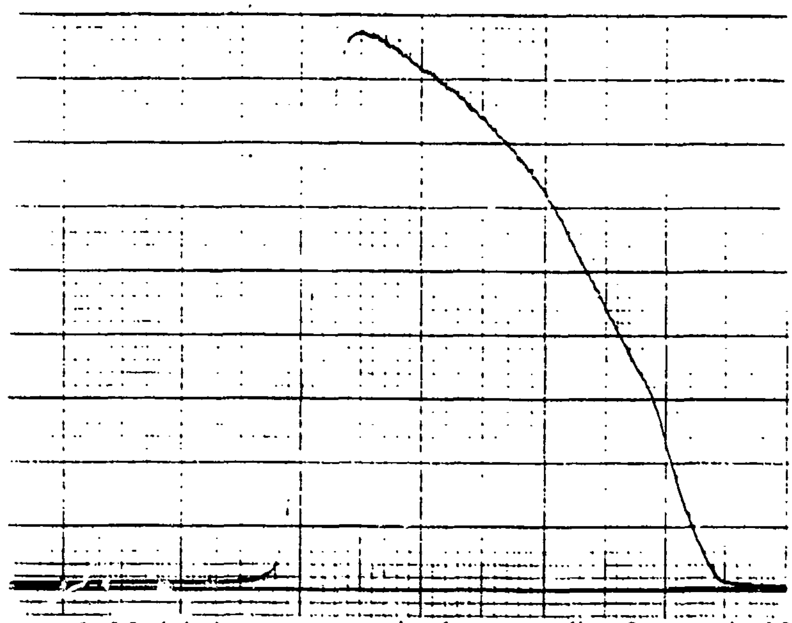

Figure 16. Modulation contrast strip chart recording for a typical NVG.

graph will show a line that starts near zero luminance at the edge of the FOV, rises to maximum luminance, then falls back to zero luminance again at the other edge of the FOV, as in Figure 15. For modulation contrast, a graph is produced that shows the luminance profile across the bright and dark areas of the split field target (Figure 16).

Intensified Field of View Analysis

A qualitative assessment of the NVG field of view can be easily extracted from the strip chart recording by comparing data acquired from a recently tested system to older data. For a more detailed, quantitative analysis, the distance between the initial and final luminance inflection points on the strip chart recording must be measured and converted to degrees using Equation 7.1,

$$\theta = (R_c)(R_d) \tag{7.1}$$

where θ is the field of view of the NVG, R_c (deg/in) is the calibration factor, and R_d is the distance between the initial and final luminance inflection points. Figure 15 illustrates the field of view for a typical NVG.

Luminance Non-Uniformity Analysis

The same strip chart recording used for the intensified field of view measurement is the basis for determining luminance uniformity across the field. If luminance were uniform, the graph would have a uniform horizontal line across the field. Luminance non-uniformity appears as a variation in the line across the chart graph, and typically is a fall-off in luminance from center to edge. Due to this fall-off and due to equipment limitations, it is difficult to measure the luminance at the edge of the goggle's FOV. Therefore, the luminance non-uniformity analysis is restricted to the central 80% of the tested system's measured field of view. Figure 15 demonstrates the luminance non-uniformity of a typical NVG.

To calculate luminance non-uniformity, three specific measurements must be taken from the graph. These are the maximum luminance, L_{max}, the luminance at the point bordering the right side of the central 80% of the measured field of view, $L_{80\%R}$, and the point bordering the left side of the central 80% of the field of view, $L_{80\%L}$. A value for luminance non-uniformity, *LNU*, expressed as a percentage, can be calculated from these numbers using Equation 7.2.

$$LNU = \frac{2L_{max} - (L_{80\%L} + L_{80\%R})}{2L_{max} + L_{80\%L} + L_{80\%R}} * 100\% \qquad (7.2)$$

The mathematical procedure required to calculate luminance non-uniformity is somewhat involved and is therefore easier to express it as a single equation. More detailed examinations of the mathematics involved in the luminance non-uniformity calculation and the derivation of this equation are available in Appendix A.

Modulation Contrast Analysis (Near Field and Far Field Contrast)

The strip chart recording from the measurement of the split field target is used to determine the modulation contrast. The data is reduced by listing near field and far field contrast, which would be the contrast measured at specified angles close to (5°) and farther from (10°) the edge of the dark field. Contrast is calculated by using the modulation contrast equation (Equation 7.3).

$$C_i = \frac{L_{max} - L_{min(i)}}{L_{max} + L_{min(i)}} \qquad (7.3)$$

C_i is the contrast calculated at i degrees from the drop-off edge, L_{max} is the measurement at the highest peak of the graph, and $L_{min(i)}$ is the measured point at i degrees from the drop-off edge. Figure 16 demonstrates the modulation contrast for a typical NVG.

7.4 Comments

These methods provide a relatively easy objective assessment of the NVG visual field parameters as long as the specifications of the procedure are followed carefully. An error will result if the parameter is not measured with an input light source which produces a uniform output and fills the entire NVG field of view. These measurements provide hard copies (Figures 7.2 and 7.3) of information which can be extracted directly from the graphs.

The analysis of the data collected using this procedure is somewhat subjective and is limited by the technician's ability to locate the points of interest accurately. Equipment limitations make an exact determination of the location of the edges of the measured FOV and the location of the light/dark border in the modulation contrast measurement is difficult. These factors must be considered when reviewing information about a tested system's visual field parameters.

COMBINER TRANSMISSIVITY

8.1 Introduction

Transmissivity is the ratio of the luminance of a light source measured through a medium to the luminance of the source measured directly (11). Some night vision goggles use a beam-splitter as an image combiner to relay the intensified image to the user. When the goggle is switched off, the combiner allows the user to see cockpit information without removing or manipulating their goggles. Combiner transmissivity is measured on these systems to determine how much of the light from the outside scene, such as an instrument panel of the cockpit, passes through the combiner.

8.2 Approach

Figure 17 depicts the equipment arrangement needed to measure the combiner transmissivity. This procedure requires a regulated light source and a telephotometer or spectral scanning radiometer.

The spectroradiometer is placed at least six feet in front of and focused on the light source. The baseline spectral radiance (or luminance if using a telephotometer) of the regulated light source is measured from 380 nm to 1000 nm at 10 nm intervals. The NVG is then positioned such that the beam splitter is between the spectroradiometer and the regulated light source. The apparent spectral radiance (or luminance depending on the instrument) is once again measured through the beam splitter from 380 nm to 1000 nm. The ratio of the radiance of the source as seen through the beam splitter to the radiance of the source viewed directly is calculated for each measured wavelength.

8.3 Results

Once the radiance values measured through the image combiner for each wavelength are known, they are divided by their corresponding radiance value from the baseline spectral scan of the light source. Fortunately the radiometer used performs this function and eliminates the need for the operator to calculate each ratio by hand. If the device used to measure transmissivity cannot handle mathematical manipulations, then the operator must calculate the percent transmissivity for numerous wavelengths to draw

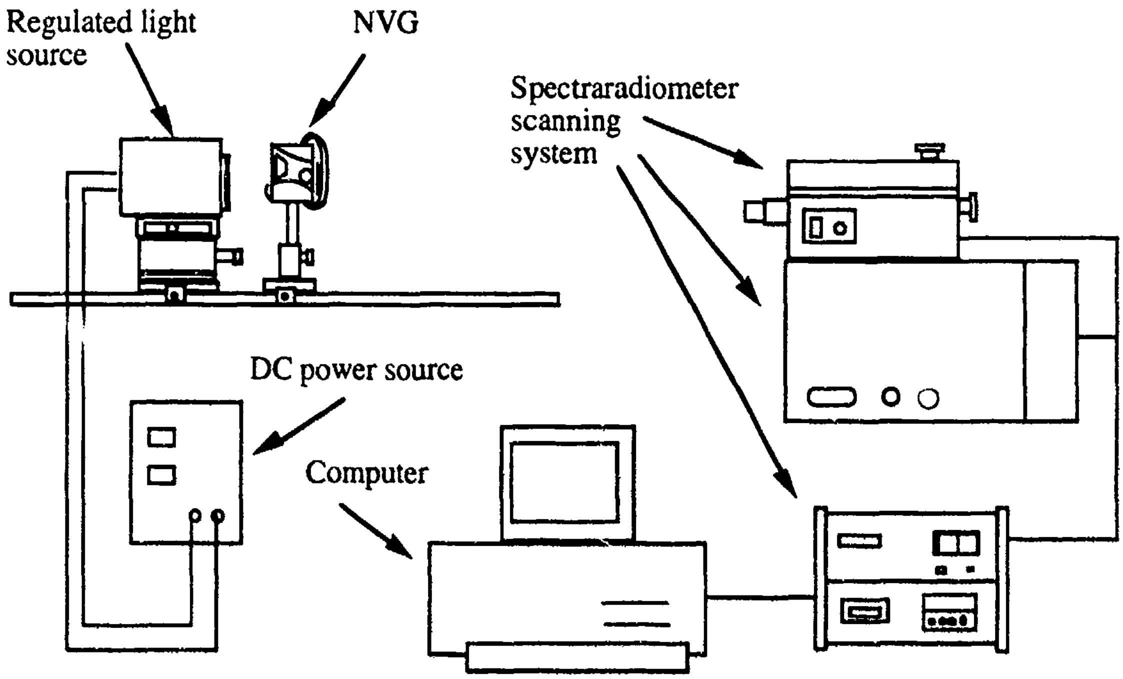

Figure 17. Test arrangement for the combiner transmissivity procedure.

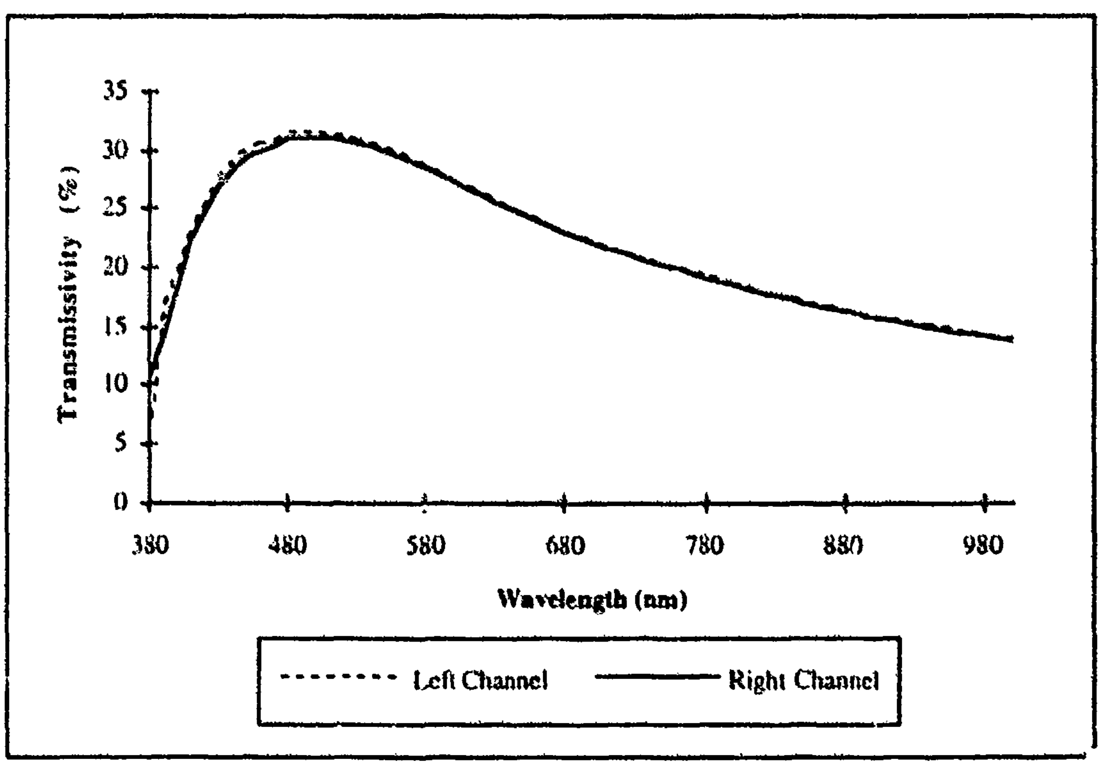

Figure 18. Example of typical NVG combiner transmissivity data.

the necessary graph. These percentages are then plotted against wavelength. Figure 18 shows a typical NVG image combiner transmissivity curve.

8.4 Comments

Figure 18 illustrates that the transmissivity of the beam-splitter at any wavelength can be determined graphically from the data collected during the procedure. Note that one must be careful of reflections and stray light sources during this measurement. Spurious light will cause erroneously high transmissivity values, if detected during the measurement of the combiner, or lower transmissivity values if detected while measuring the source baseline.

UNINTENSIFIED FIELD OF VIEW

9.1 Introduction

The unintensified field of view is a measure of how much the eye can see outside the intensified field of view of the NVG. It is simply a measure of peripheral vision and is concerned strictly with the observation around the NVG. For NVGs which have a combiner as an eyepiece, this measurement will also include the unintensified field of view as seen through it.

9.2 Approach

This procedure requires the use of a field perimeter, a holding fixture for the NVGs, and trained observers. Figure 19 depicts the arrangement of the equipment and the position of the subject.

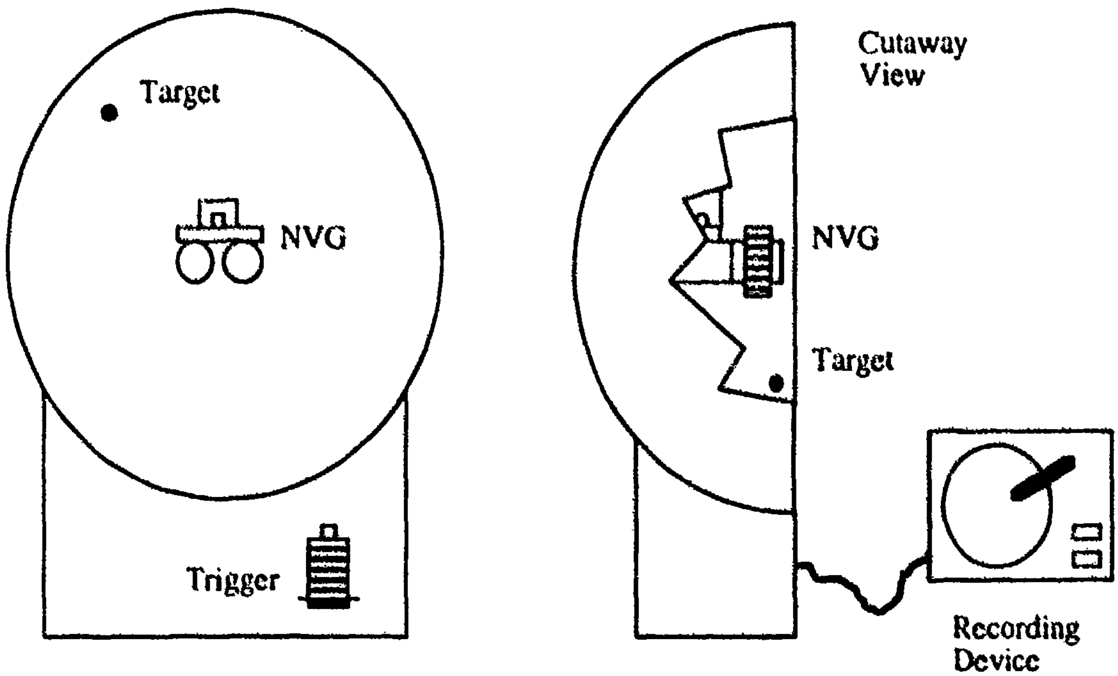

Figure 19. Test arrangement for the unintensified field of view measurement.

The NVG is mounted to the field perimeter so that the eye position of the observer is both in the correct eye position for wearing the NVG and in the correct position for measuring the peripheral field of view. The point light target of the field perimeter is positioned outside the field of view of the observer and brought radially inward toward the eye position until the observer can see it. The angle at which the point becomes visible is recorded on a field map for the meridian measured. This is repeated every 15 degrees until a full map of the field of view is obtained. This is measured for both the right eye position and the left eye position. A measurement without the NVG is also taken to provide a baseline graph. The results are typically recorded in units of steradians.

9.3 Results

Figure 20 is an example of a typical perimeter field graph. The number of steradians that are available to the observer without the NVG (baseline graph) is compared to the graph produced with the NVG. It may be possible to determine from the chart what limits the visual field, facial features or the NVG. Once that information is obtained, the results are then expressed as a percentage, such as the unintensified FOV with the NVG is 87% of the baseline without the NVG. The number of steradians available with the NVG is also recorded.

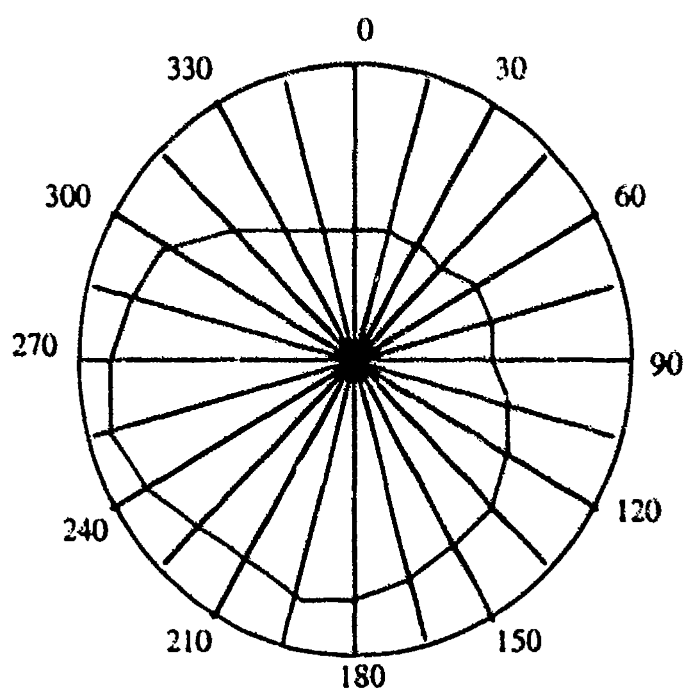

Figure 20. Example of typical perimeter field graph.

9.4 Comments

This is a highly subjective measurement. It relies on the use of a human observer in addition to an operator of the field perimeter. The results will vary considerably with the facial features of the subject and with the use or lack of chemical, biological, and neurological protective equipment.

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APPENDIX A

Derivation of the Luminance Non-Uniformity Equation

In the section of this report discussing the evaluation of NVG visual field parameters, an equation was given to compute the percent luminance non-uniformity of a system from three measurements made from a chart recorder trace (Equation 7.2). The origin of this equation is not perfectly obvious. This appendix will closely examine the luminance non-uniformity calculation and show the validity of Equation 7.2.

Luminance non-uniformity is a comparison of the actual luminance profile of an NVG image to an ideal, flat, uniform luminance value. It can be expressed either as a percentage, as in this report, or as a ratio of center FOV luminance to edge FOV luminance, as in the ANVIS image intensifier assembly specification. Equipment limitations make measuring the luminance output at the extreme edge of the intensified image difficult. Because of equipment limitations and measurement difficulties, the evaluation is limited to the central 80% of the tested NVG's field of view.

The calculation, expressed as a percentage, requires a low end, a mean, and a maximum luminance value. The maximum value can be measured directly from the chart recorder trace and is denoted as L_{max}. The other values are not as easily acquired.

The minimum luminance value can be found by comparing $L_{80\%L}$ and $L_{80\%R}$. These are the luminance values at the left and right most points, respectively, which define the central 80% of the NVG's measured field of view. The locations of these measurements on a typical chart recorder trace are shown in Figure A-1. Ideally, the field of view chart recorder trace, from which these measurements are taken, should be symmetric. Therefore, $L_{80\%L}$ and $L_{80\%R}$ should equal each other and equal the minimum luminance value. Unfortunately, this is rarely the case. The minimum luminance value, L_{low}, is then calculated as the average of the two, as in Equation A.1.

$$L_{low} = \frac{L_{80\%L} + L_{80\%R}}{2} \tag{A.1}$$

The mean luminance value, L_{mean}, is calculated by averaging the maximum luminance value and the minimum luminance value, as in Equation A.2.

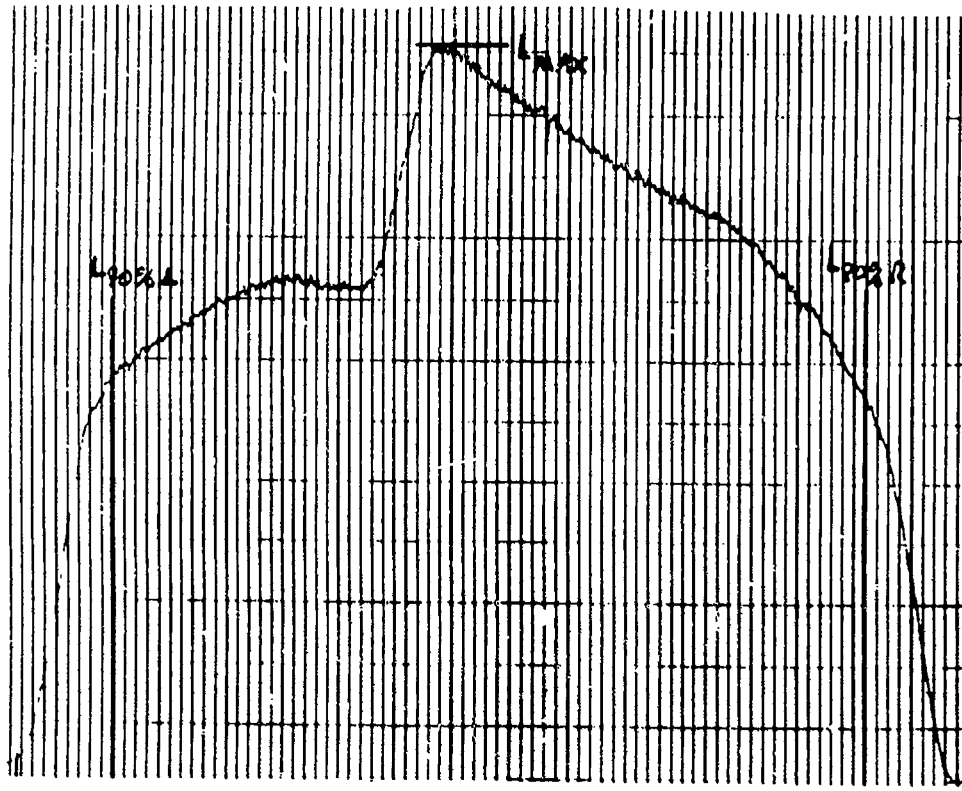

Figure A-1. Chart recorder trace used to determine luminance non-uniformity.

$$L_{mean} = \frac{L_{max} + L_{low}}{2} \tag{A.2}$$

Substituting Equation A.1 into Equation A.2 yields

$$L_{mean} = \frac{2L_{max} + L_{80\%L} + L_{80\%R}}{4} \tag{A.3}$$

The actual luminance non-uniformity value, *LNU*, is then calculated taking the difference of the maximum luminance value and the mean luminance value, dividing by the mean luminance value, and multiplying by 100% to express it as a percentage (Equation A.4).

$$LNU = \frac{L_{max} - L_{mean}}{L_{mean}} * 100\% \tag{A.4}$$

Substituting Equation A.3 into Equation A.4 will yield a luminance non-uniformity equation in terms of only L_{max}, $L_{80\%L}$, and $L_{80\%R}$ equal to Equation A.5.

$$LNU = \frac{2L_{max} - (L_{80\%L} + L_{80\%R})}{2L_{max} + L_{80\%L} + L_{80\%R}} * 100\% \quad (A.5)$$

This evaluation is quicker and easier to use than running the entire calculation for each ocular of each goggle evaluated and reduces the possibility of mathematical error.

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